Ext-Win DA: the next ECMWF operational data assimilation system for time-critical applications



Emiliano Orlandi

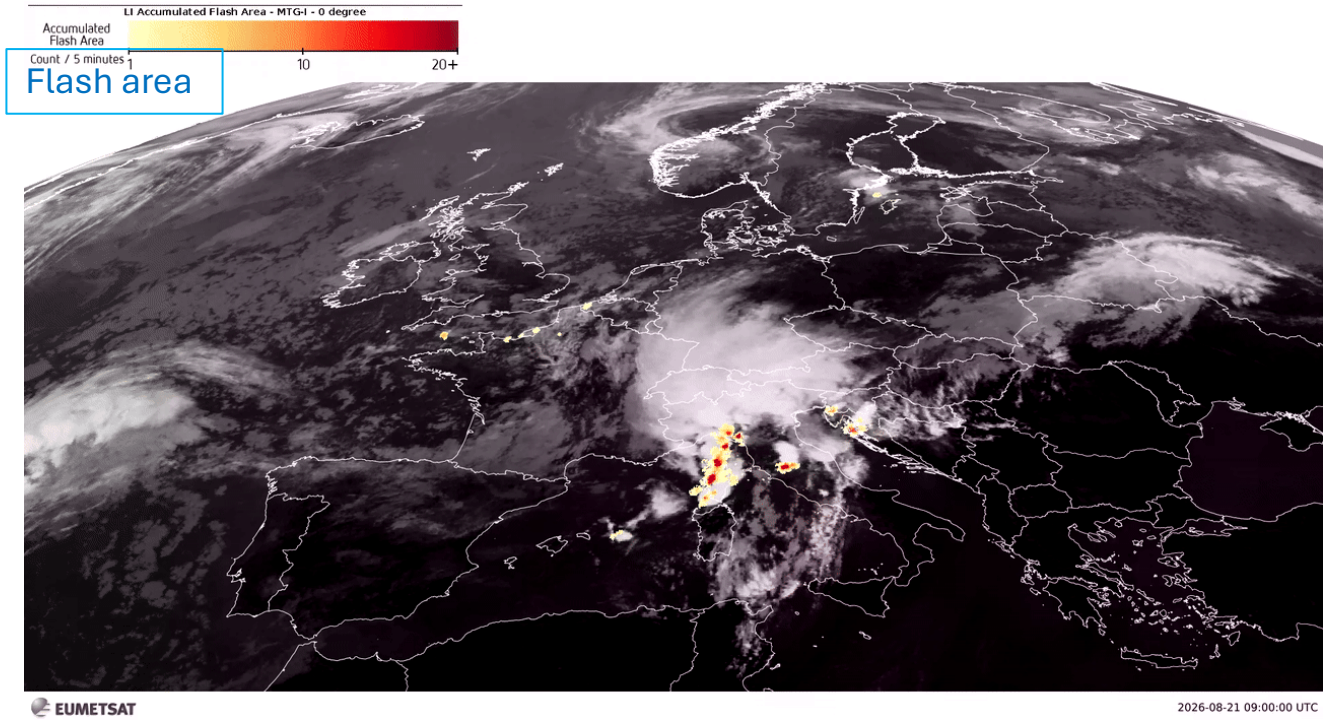
In collaboration with M. Bonavita, P. Lean, E. Holm, J. Banderas,

N. Bormann, I. Pasmans, S. Massart, T. McNally, R. Osinski, S. Villaume,

M. Fuentes, J. Hodkinson, and others

Funded by the European Union Destination Earth implemented by ECMWF esa EUMETSAT

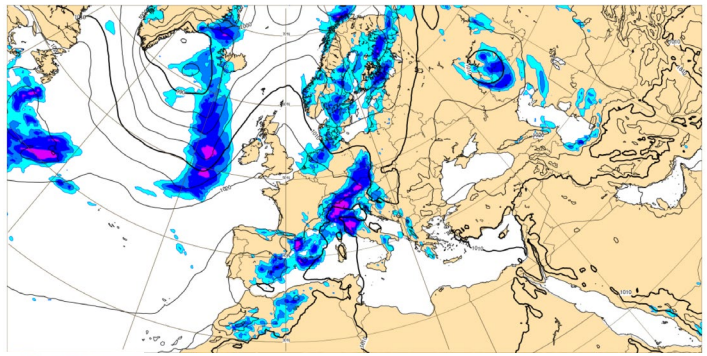
Continuous observations and discrete analysis cycles

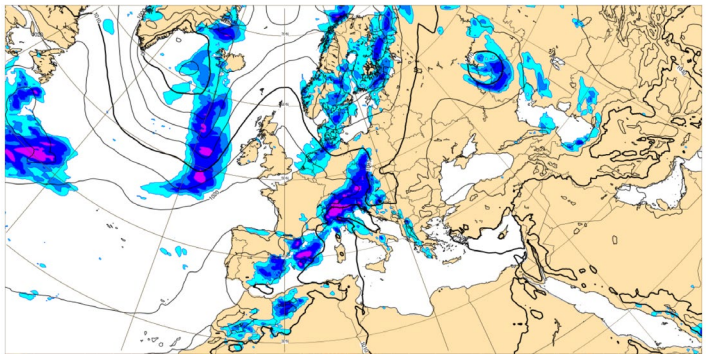


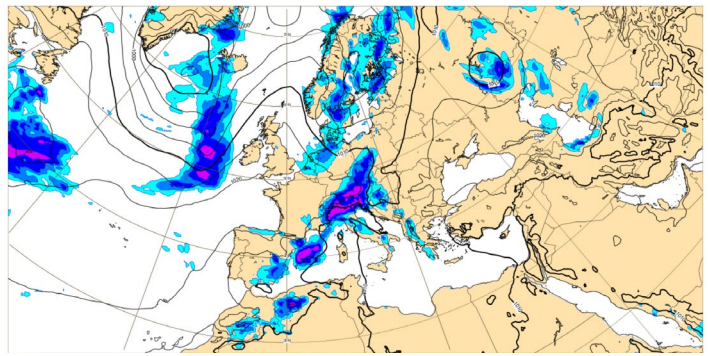
Observations are collected and distributed **continuously** with high **timeliness**

Global **atmospheric analyses** are updated every 6 hours

20260909 18:00 UTC







Total precipitation over last 6H (mm)



Closing the gap

- 6 hourly global analysis → Regional analysis (<6H) → Limited-area forecast

  + latest observations

RAP / KENDA / UKV / AROME France / JMA-LA



Risk management
Energy
Transport
Agriculture
Commodity trading
…

Closing the gap

- 6-hourly global analysis + latest observations → Regional analysis (<6H) → Limited-area forecast

  RAP / KENDA / UKV / AROME France / JMA-LA

- 6-hourly global analysis + latest observations → Observation-augment AI forecasts (≤ 6H update)

  WeatherNext 3 Sky1 Weather Generator

- Observations only → Direct observation-to-forecast AI (≤ 6H update)

  AIFS-DOP / HealDA / AIDA / WeatherMesh-6

Risk management
Energy
Transport
Agriculture
Commodity trading
...

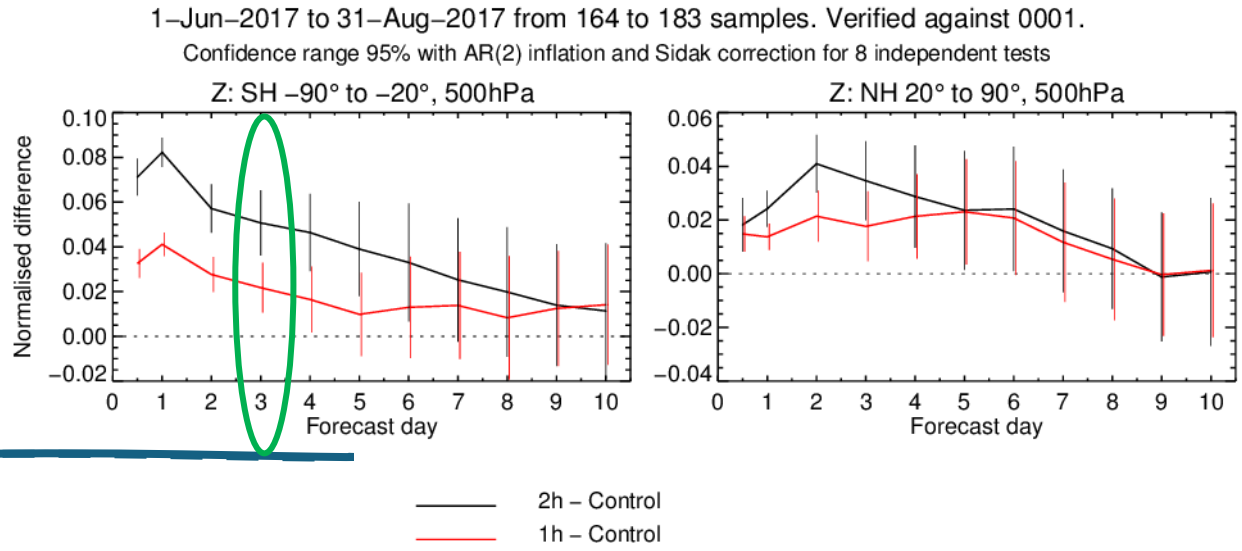
Extending window DA provides a pathway to more frequent **global analyses** within the established 4D-Var framework.

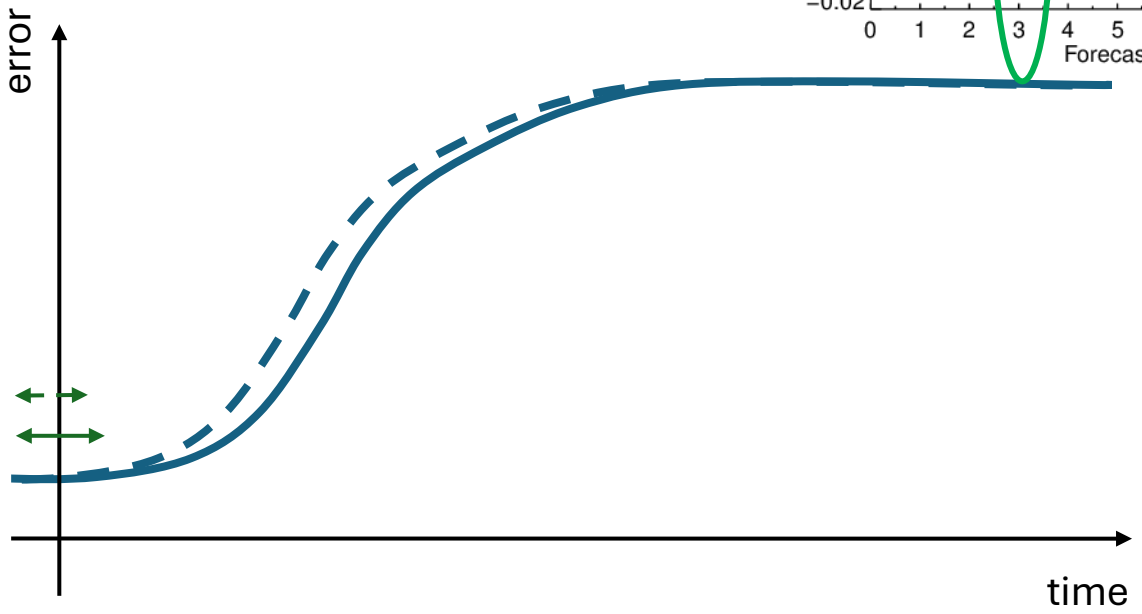
Outline

- Path to Extending-Window Data Assimilation
  1. Continuous DA at ECMWF
  2. Combining short- and long-window data assimilation

- Towards More Frequent Analysis Updates
  1. Extending Window DA concept
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  4. Computational footprint

What is the value of 1 hour of observations at the end of the window?





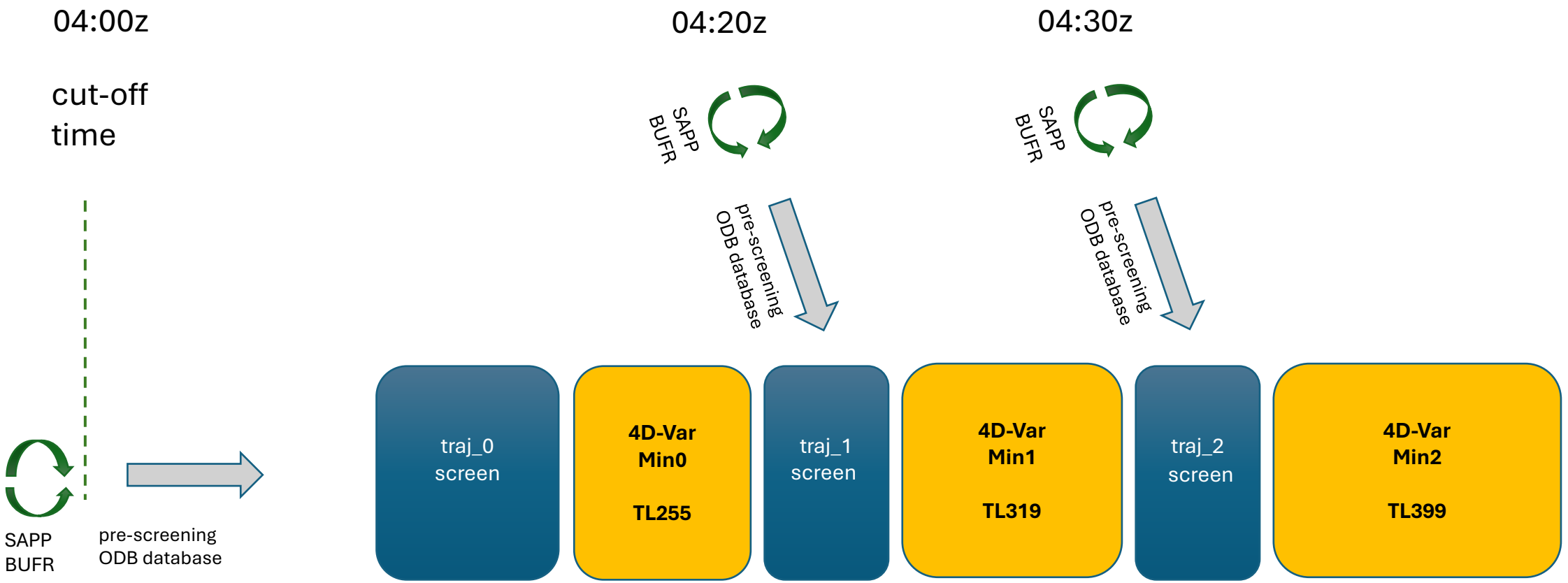
Errors constrained by observations within assimilation window

LWDA experiment blacklisting all observations in **last hour (red)** and **last 2 hours (black)** of the assimilation window

Peter Lean

Add newly arrived observations each outer loop

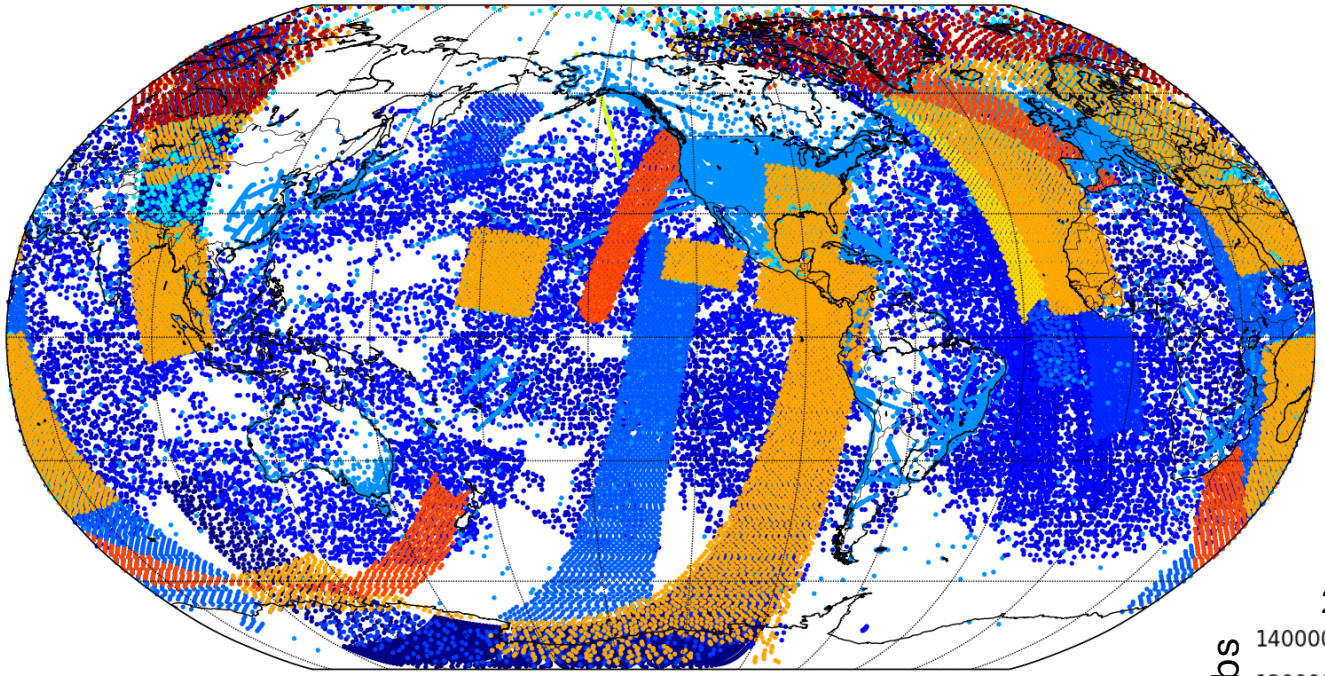
IFS cycle 46R1 – 2019

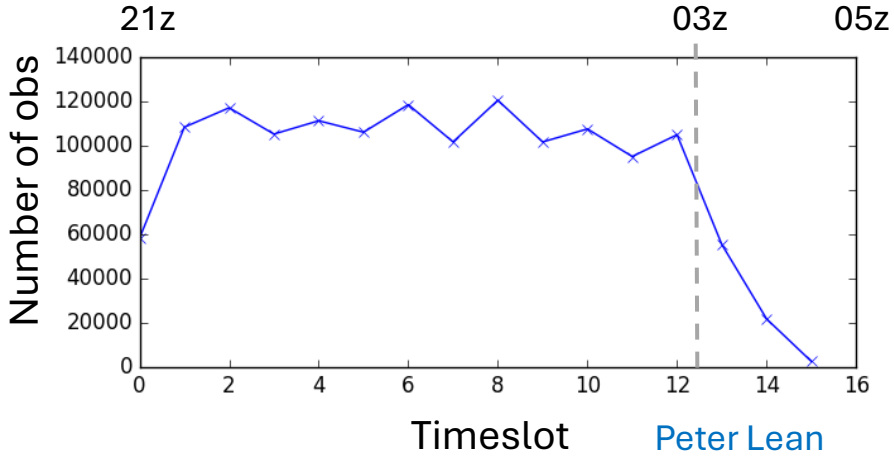


- Progressive observations cutoff
- Longer DA window (from 6H to 8H)

Peter Lean

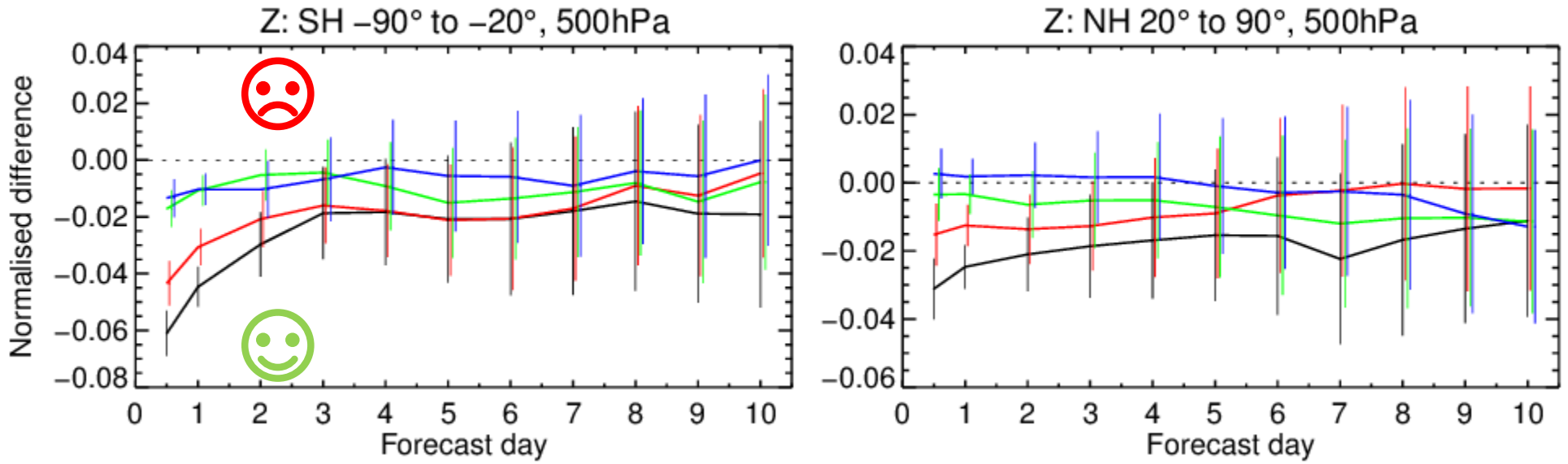
Extra observations assimilated in Continuous DA configuration





Peter Lean

Where do the improvements come from?



Control:

- 3 outer loops
- 6H DA window

Late cut-off only

8hr window only

8hr window + late cut-off

4 outer loop + 8hr window + late cut-off

Peter Lean

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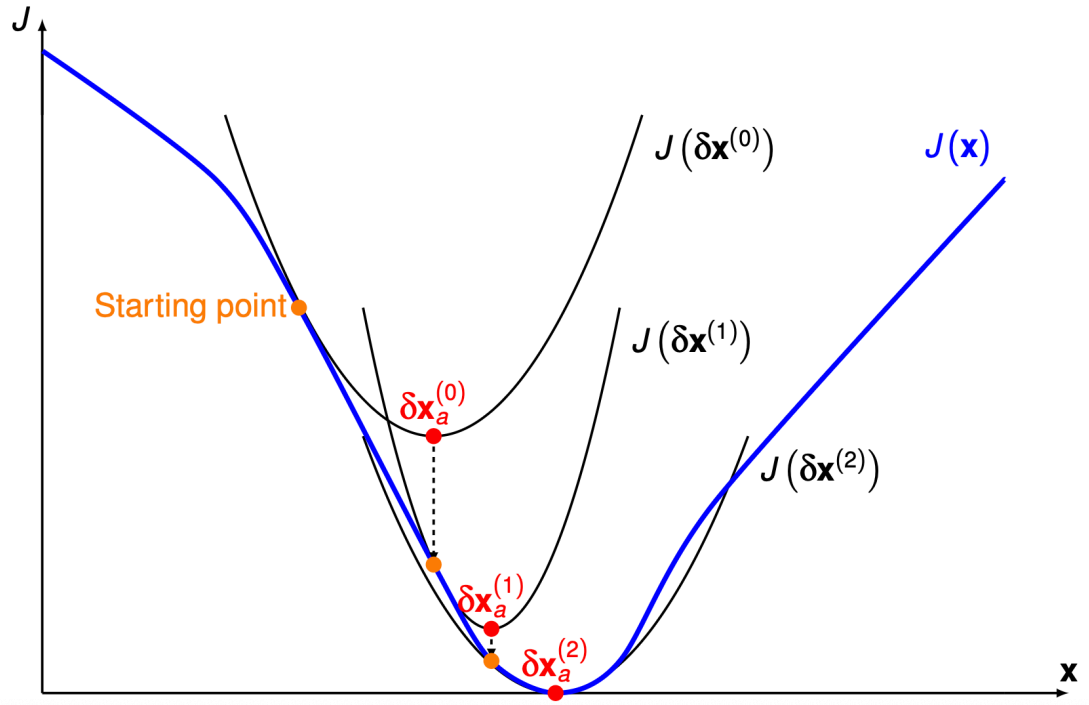
Atmospheric data assimilation at ECMWF: Incremental 4D-Var

Incremental 4D-Var approximates the minimisation of a nonlinear cost function through a sequence of quadratic cost functions.

These are obtained by **repeatedly linearising** the forecast model and the observation operators around progressively more accurate guess value of the solution.

ECMWF implementation: the successive quadratic minimisation problems are solved at progressively **higher horizontal resolutions**.

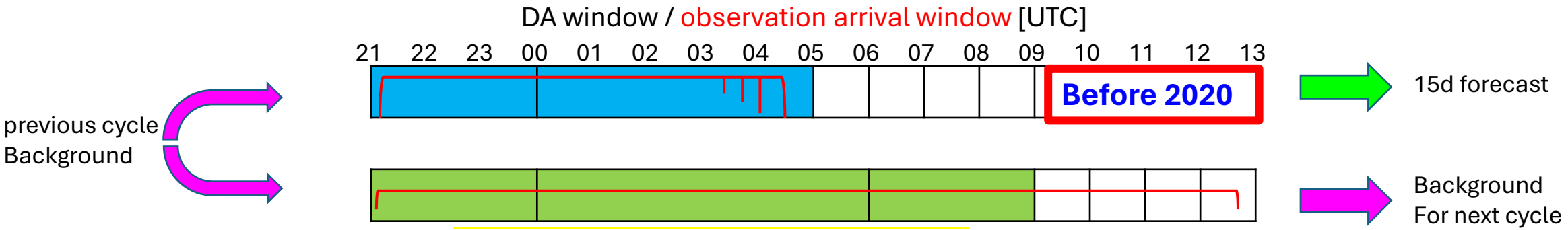
- **Outer Loop (OL):** linearization around a guess trajectory. Iterated to approach the nonlinear solution.
- **Inner loop**: iteratively minimises the quadratic cost function at progressively higher resolutions across OL



Combining short and long window DA

Before 2020:

- Two separate analyses
  - 8H window: using continuous DA / 4 outer loops / used to initialize the 15 day forecast
  - 12H window: fixed observation cutoff / 4 outer loops / used to produce the best analysis used as background for the next cycle



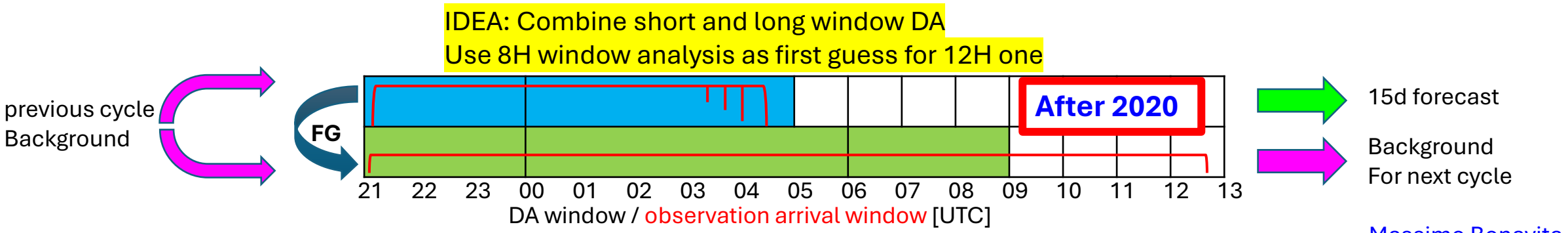
NOTE: the background AND the initial linearization trajectory are the SAME for the 8H and 12H analyses

Combining short and long window DA

After 2020:

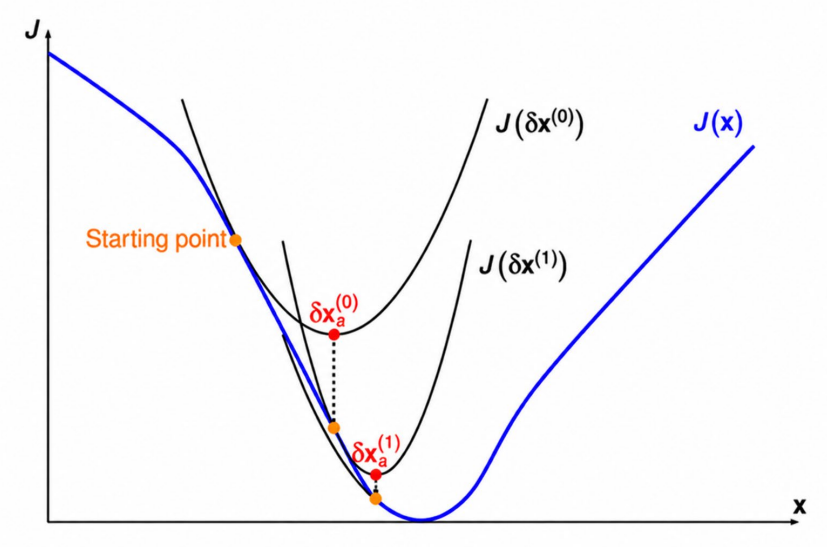
- Combine the 2 analyses: use the 8H analysis as initial linearization trajectory for the 12H window analysis

NOTE: the **background** is the same for both the analyses BUT
the initial **linearization trajectory** are now DIFFERENT for the 8H and 12H analysis



Massimo Bonavita
Elias Holm

Combining short and long window DA



IDEA: Combine short and long window DA
Use 8H window analysis as first guess for 12H one

previous cycle
Background

FG

After 2001

21 22 23 00 01 02 03 04 05 06 07 08 09 10 11 12 13

DA window / observation arrival window [UTC]

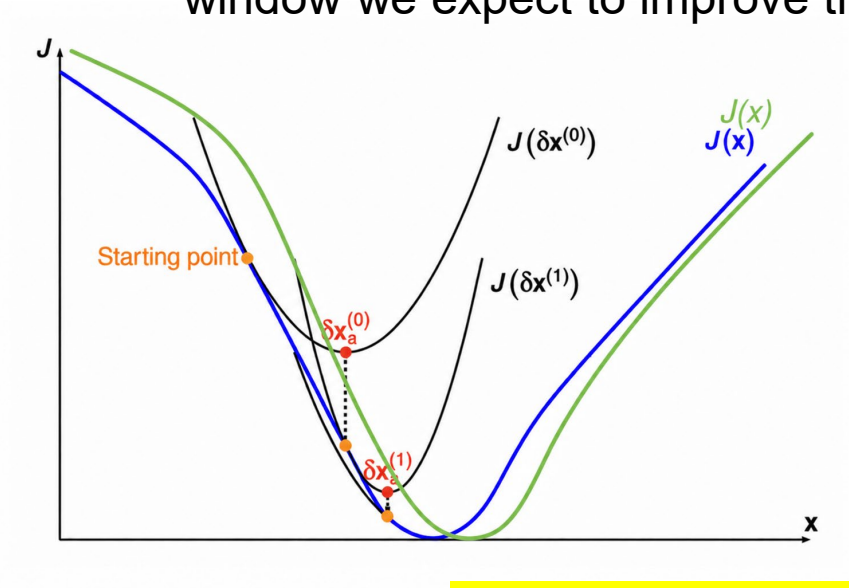
15d forecast

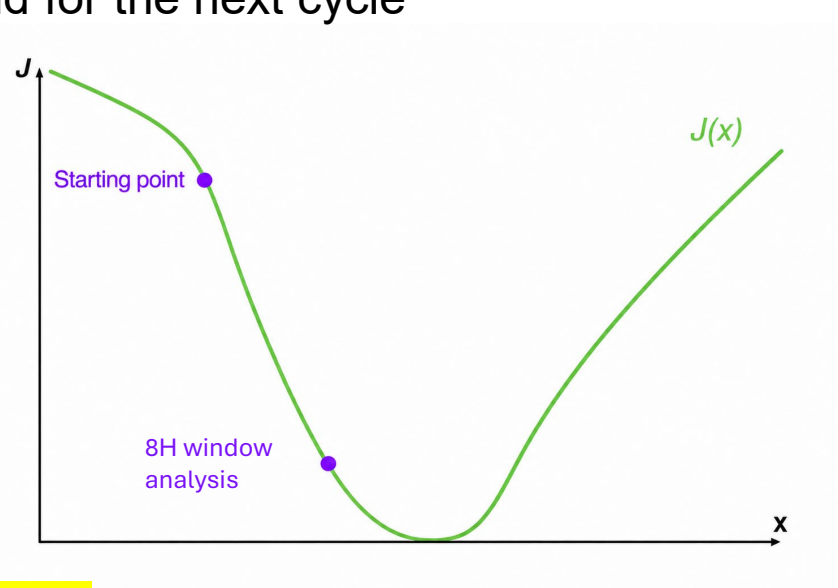
Background
For next cycle

Massimo Bonavita
Elias Holm

Combining short and long window DA

Using the 8H analysis state as linearization trajectory for the 12H DA window we expect to improve the background for the next cycle

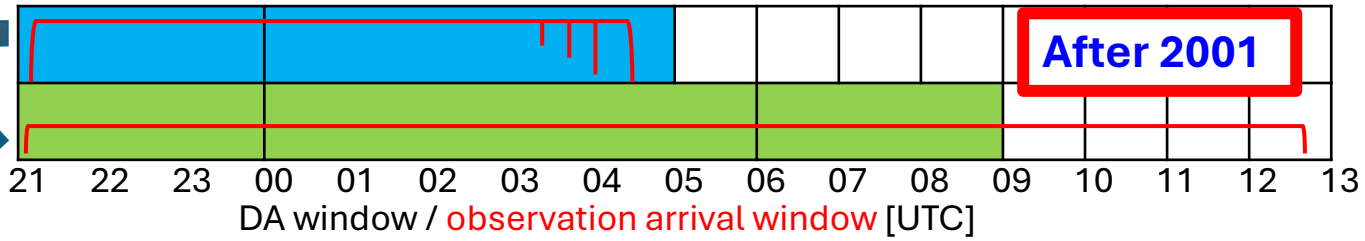




IDEA: Combine short and long window DA
Use 8H window analysis as first guess for 12H one

previous cycle
Background

FG



15d forecast

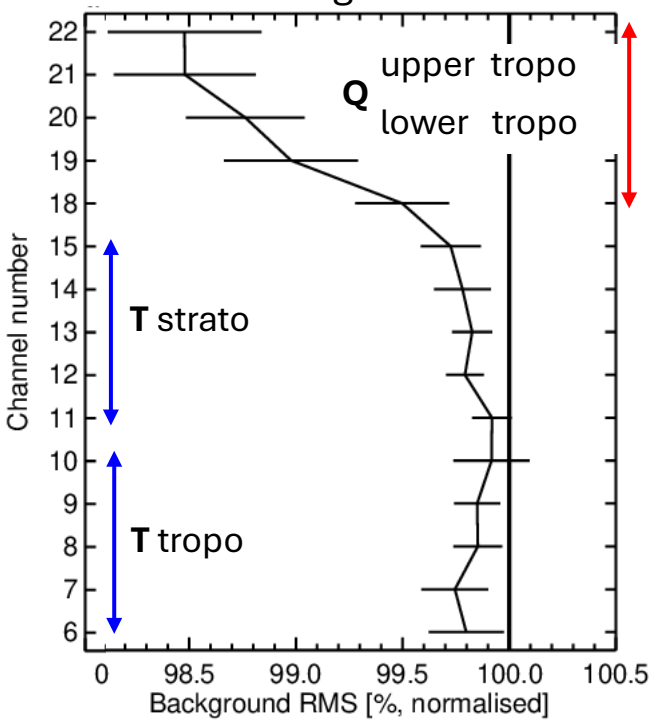
Background
For next cycle

Massimo Bonavita
Elias Holm

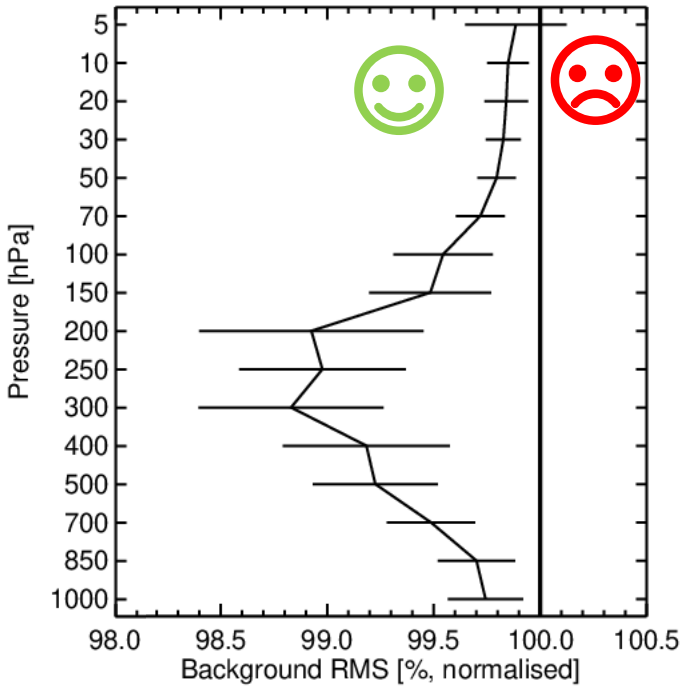
Combining short and long window DA

Comparing forecast for short and combined short-long DA window

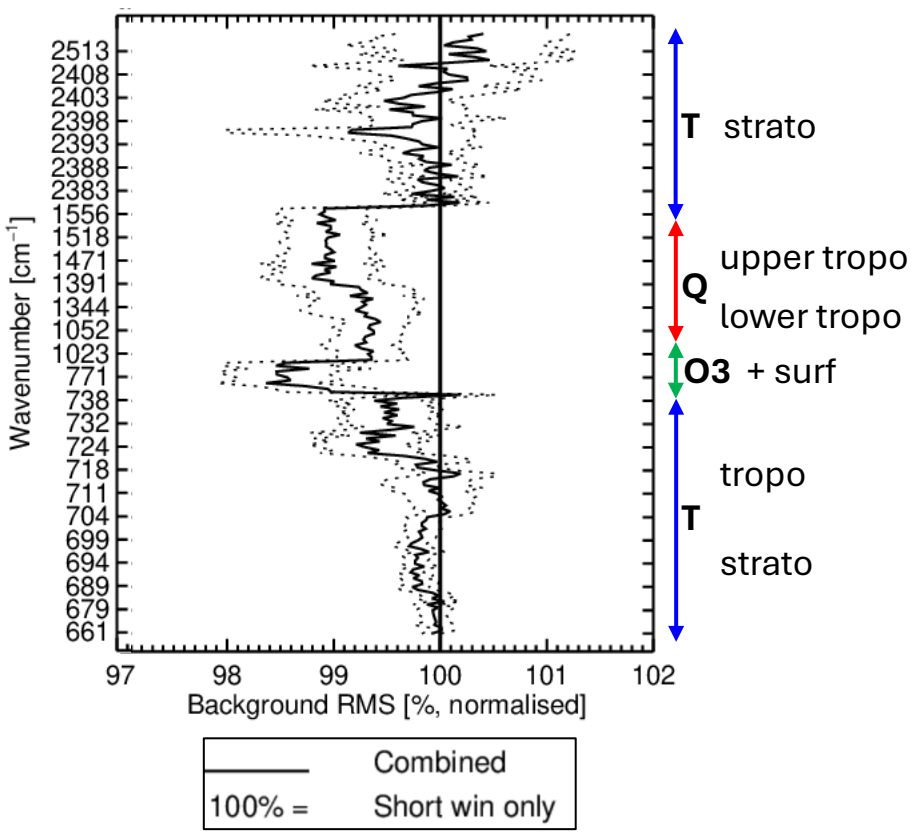
ATMS - global



Conventional wind - global



Hyperspectral IR - global



- Short-range forecast skill improved through a better background

Intro conclusions

- Continuous data assimilation **reduces the latency of observations**
  - Before continuous DA: by the time the analysis is ready, latest observation used were 2 hours old
  - After introducing **continuous DA** latency is reduced to 30 minutes

- Combined minimisation from 2 analyses (long / short window DA)
  - Improves forecast skill through a better background

- The frequency of update is still 6 hours…
  - Extending Window DA

Outline

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Towards More Frequent Analysis Updates

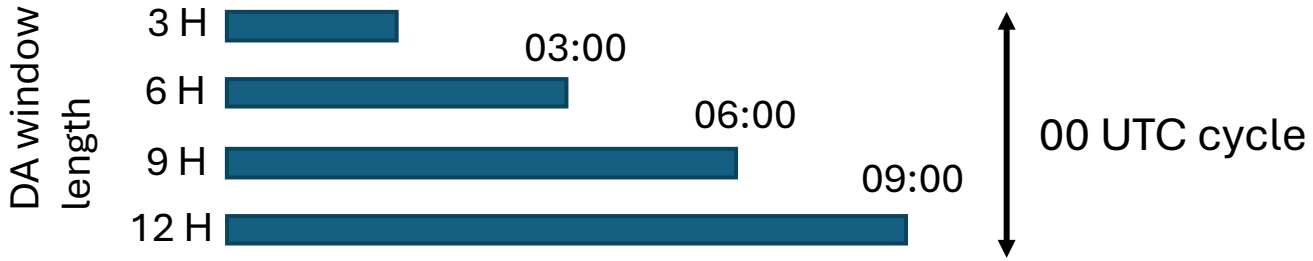
- **Global analyses and forecasts** initialize and provide lateral boundary conditions to physics- and AI-based forecast models.
- Most **WMO World Meteorological Centres** produce global analyses 4 times daily, despite the continuous flow of observations.
- **Many downstream systems** are moving towards more frequent – often hourly – update cycles.
- **Benefits** for downstream applications include**:**
  - **Prediction of rapidly evolving extremes**: the latest observations can improve short-range forecast and confidence in issuing warnings.
  - **Renewable-energy generation**: updated wind and cloud information can improve short-term power forecasts and support grid balancing.
- **Growing efforts** across public institutions and the private sector aim to produce more frequent analysis and forecast updates.
- **Challenge**: increase the global analysis update frequency using established data-assimilation methods.



Extending window DA

DA system with configurable window length

Within the same DA cycle, minimise the cost function on progressively longer windows



Each **window** produces an **updated analysis** using the **latest observations** available

The analysis produced in (*n-1*) window is used as **first guess** for next analysis update (*n)*

Background and background errors are the same within the cycle

Overarching objectives

Increase analysis update frequency

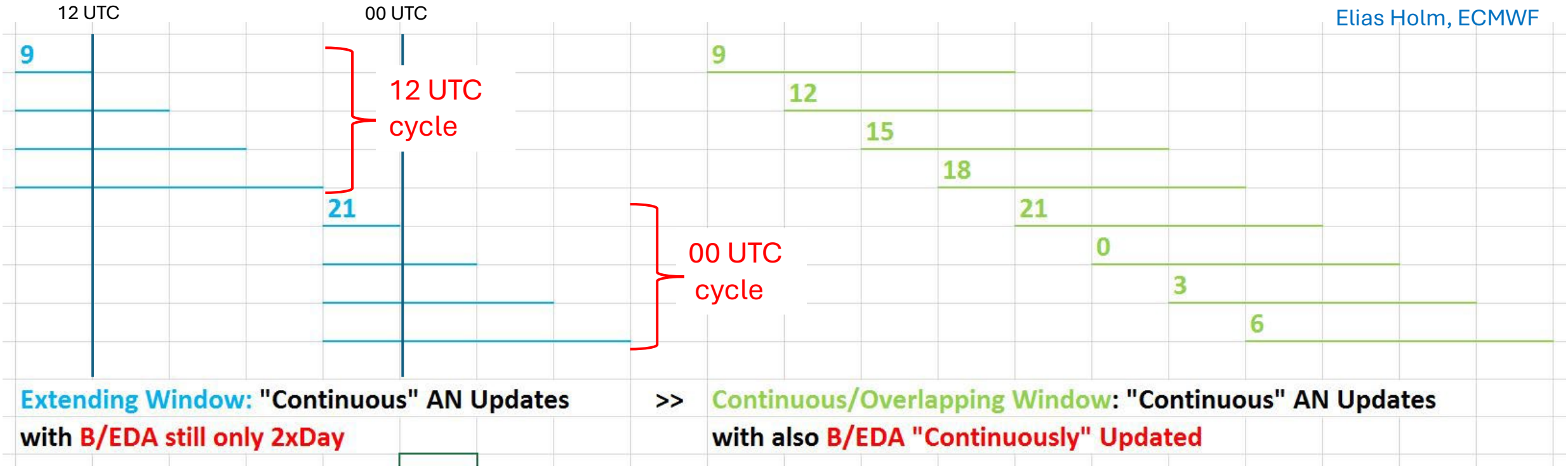
Improve forecast scores

Uniformly distribute use of computational resources over time

Towards More Frequent Analysis and EDA Updates

There are 2 paths to pursue more frequent analysis and forecast updates:

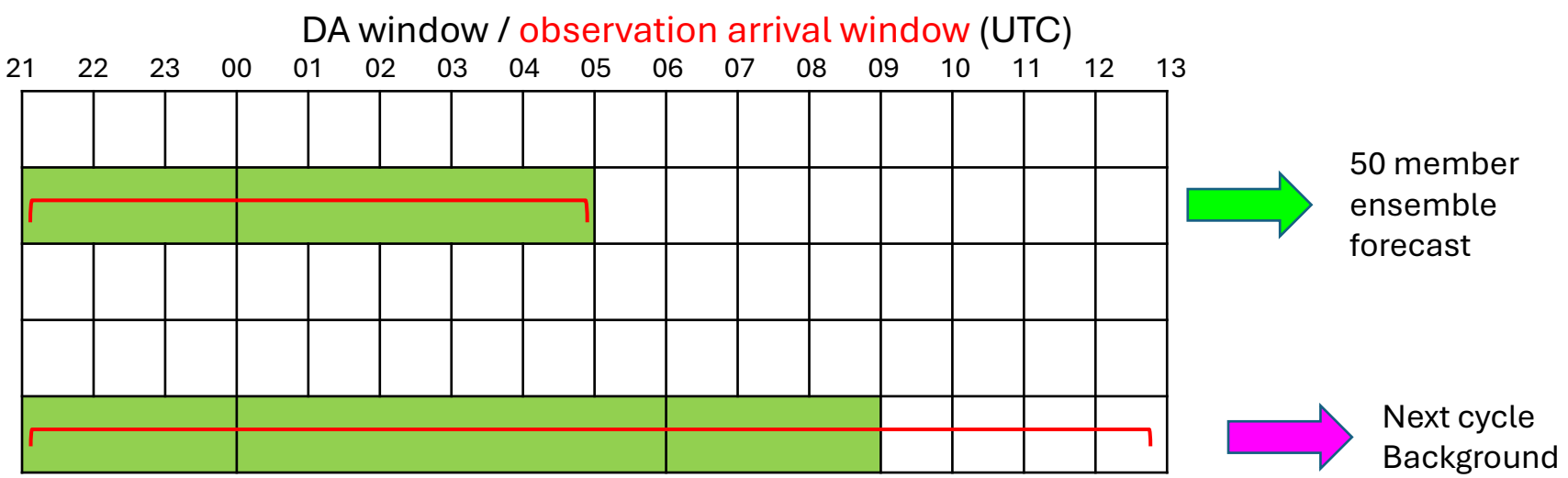
- **Extending window** → EDA still only 2xDay
- **Continuous overlapping windows** → requires more frequent EDA updates as well
- More frequent EDA's require supercharged efficiency gains → **Emulate EDA members** from a small subset of full resolution EDA members (Wei Pan talk)



12 hourly update frequency

name	Trajectory resolution	DA window length (H)	Analyses / forecasts	Outer loop count	Outer loop 1	Outer loop 2	Outer loop 3	Outer loop 4
Control	TCo1279 (9 km)	8/12	2 / 1	8	TL255 (~80km)	TL319	TL399	TL511 (~40km)

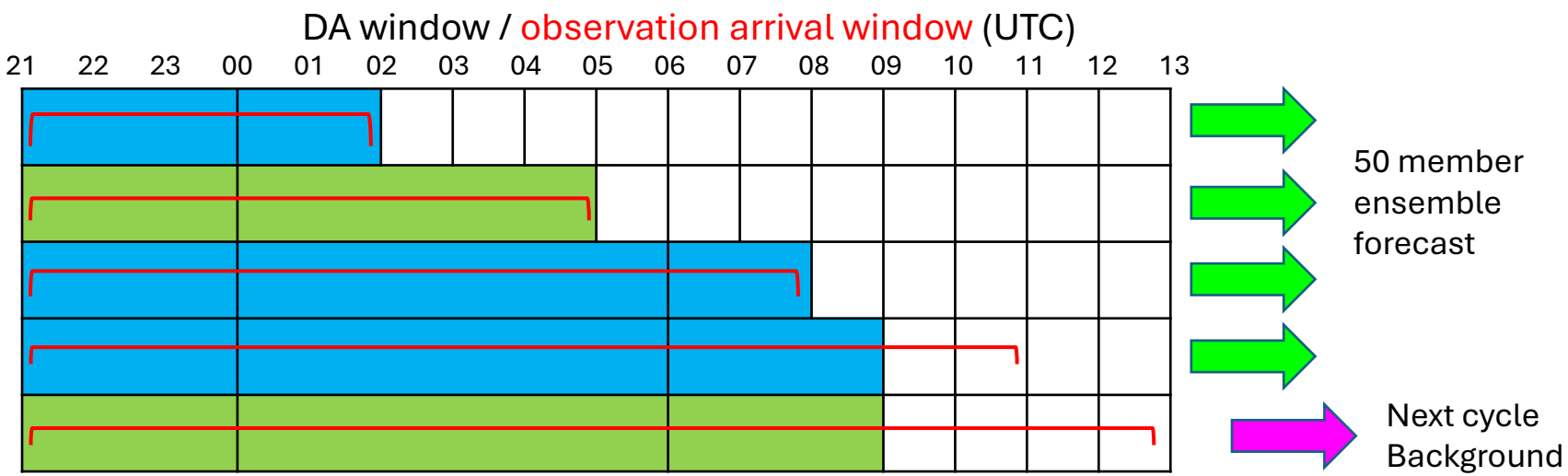
Ext Win	Contr	Window lengh (H)
	✓	8
	✓	12



3 hourly update frequency

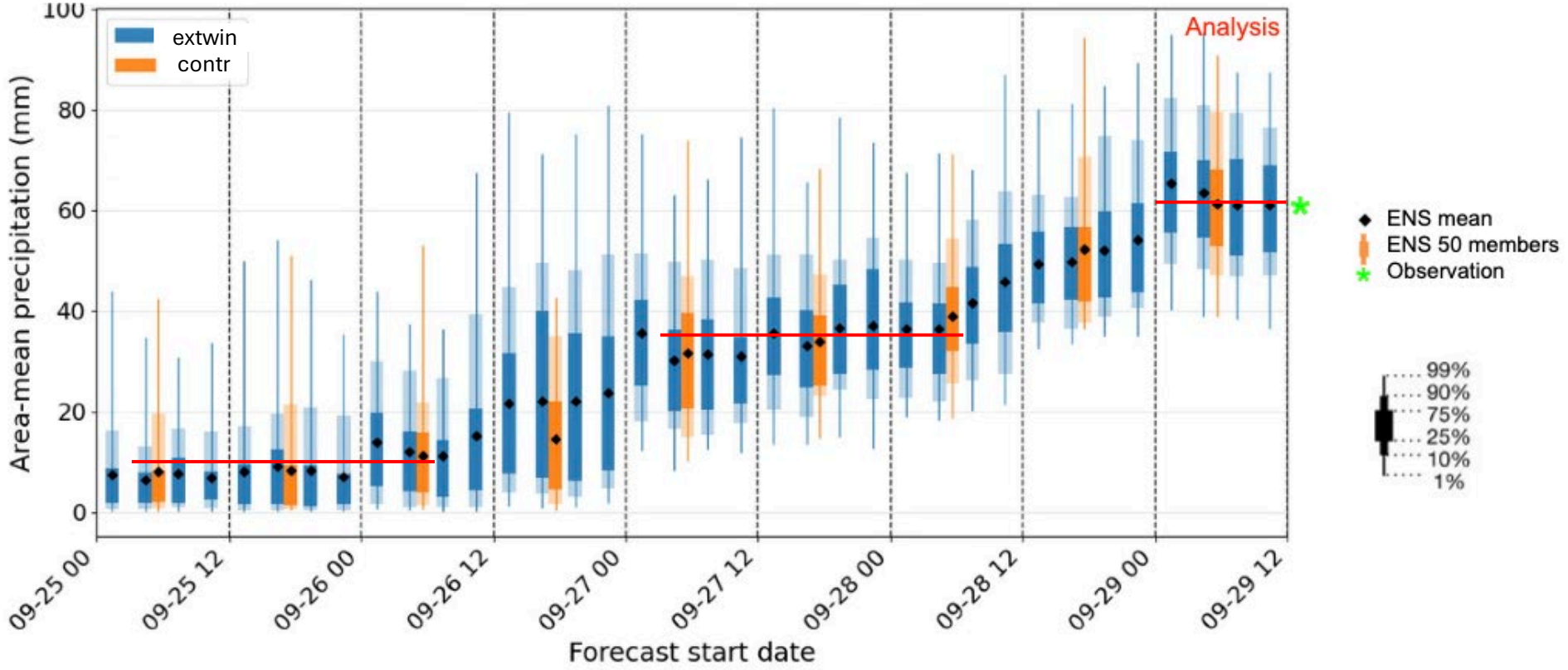
name	Trajectory resolution	DA window length (H)	Analyses / forecasts	Outer loop count	Outer loop 1	Outer loop 2	Outer loop 3	Outer loop 4
Ext Win	TCo1279 (9 km)	5/8/12/12	5 / 4	20	TL255	TL319	TL399	TL511
Control	TCo1279 (9 km)	8/12	2 / 1	8	TL255 (~80km)	TL319	TL399	TL511 (~40km)

Ext Win	Contr	Window lengh (H)
✓	✗	5
✓	✓	8
✓	✗	11
✓	✗	12
✓	✓	12



3H analysis update

202509 Valencia
1day total precipitation on 29 Sep

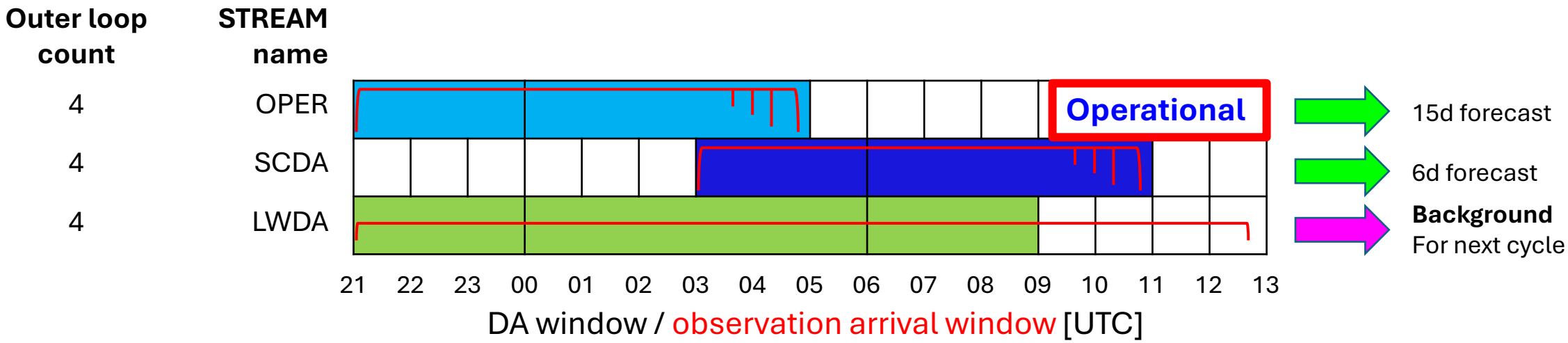


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IFS operational Data Assimilation system



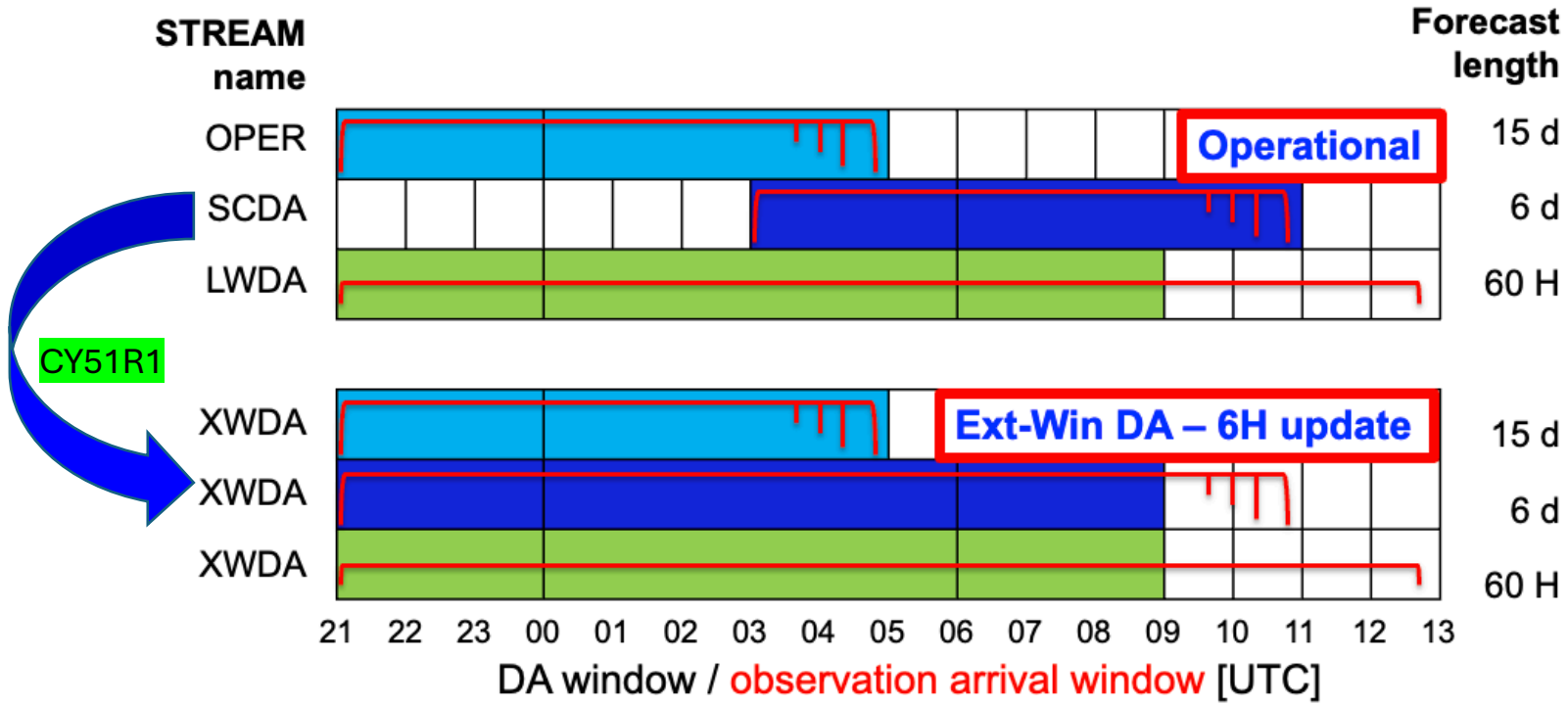
Extending Window DA

Goals

- Simplify DA system
- Improve forecast scores
- Better distributed HPC workload

Status

- Research version available for testing
- Proposed for next IFS version - **CY51R1**
  - 6H update version
  - Neutral to positive impact against operational setup



OPER, SCDA, and LWDA integrated in one single DA system

Outline

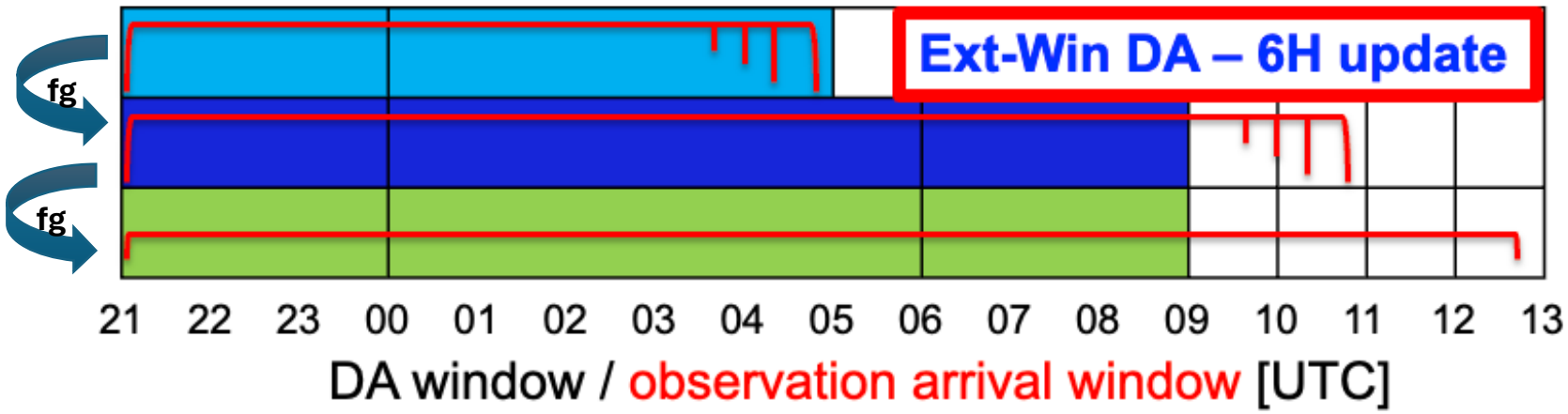
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Operational implementation: next IFS cycle

- outer loop count: 4 OL for **8H window** + 4 OL for **first 12H**
- At Increasing inner loop resolution: 78, 63, 50, 40 km

Outer loop count
4
4
1

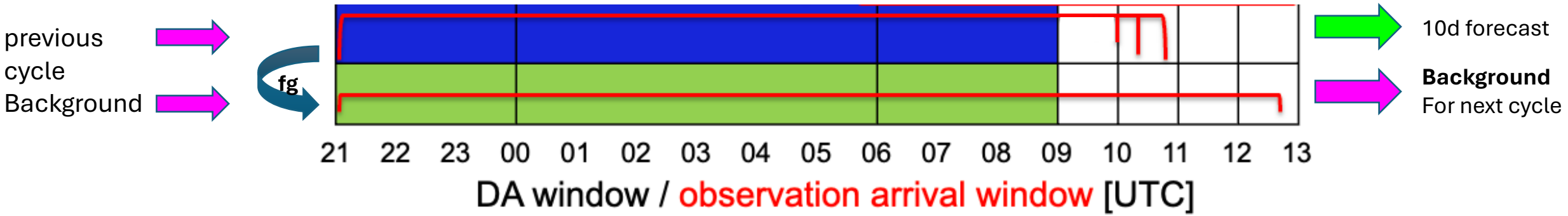


➢ Single OL for last analysis

Single OL for last analysis

Focus on 2nd part of the analysis suite
Low resolution experiments
Inner loop res: TL95/TL127/TL159 | Trajectory @ TCo399

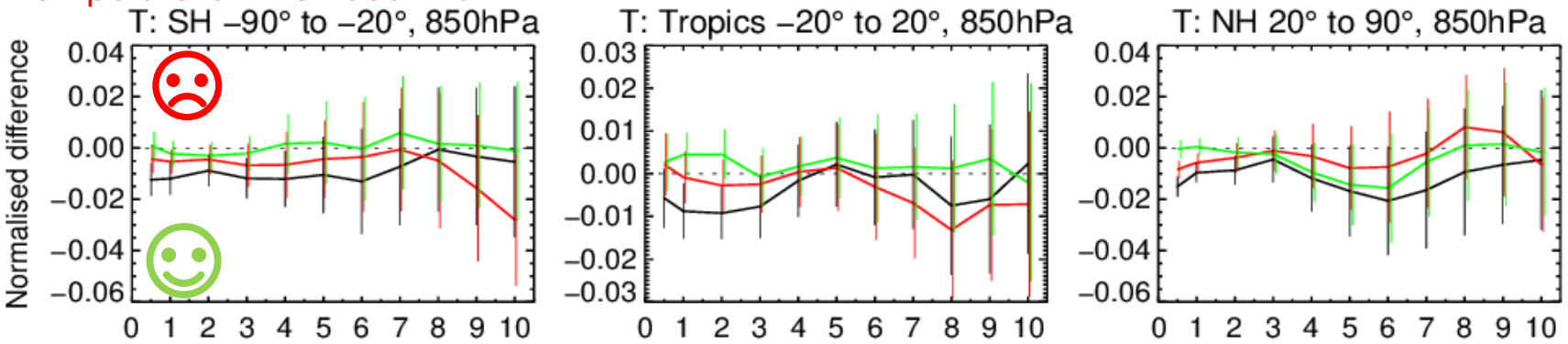
- Control: **3 + 3** outer loops
- Test: **3 + 1** outer loops @ higher inner loop resolution (TL159 or TL255 or TCo255)



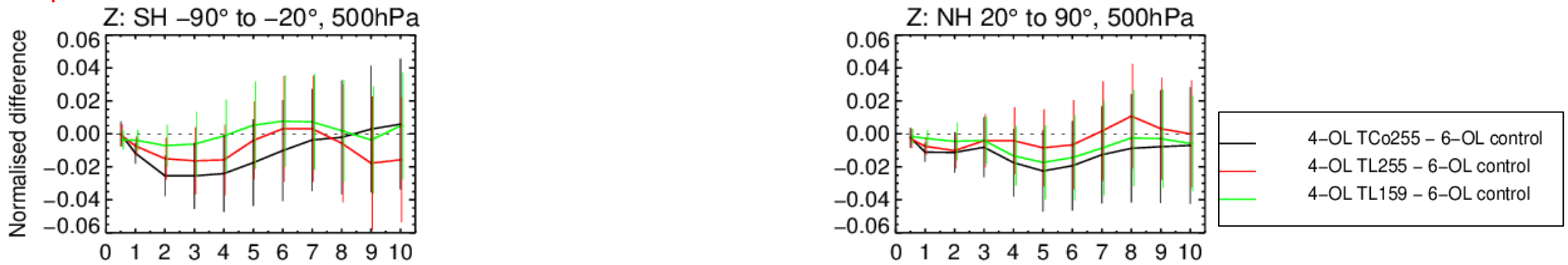
- ➢ Validate single OL
- ➢ Impact of an improved background on next cycle forecast skill

Impact on forecast skills

Temperature RMSE 850 hPa



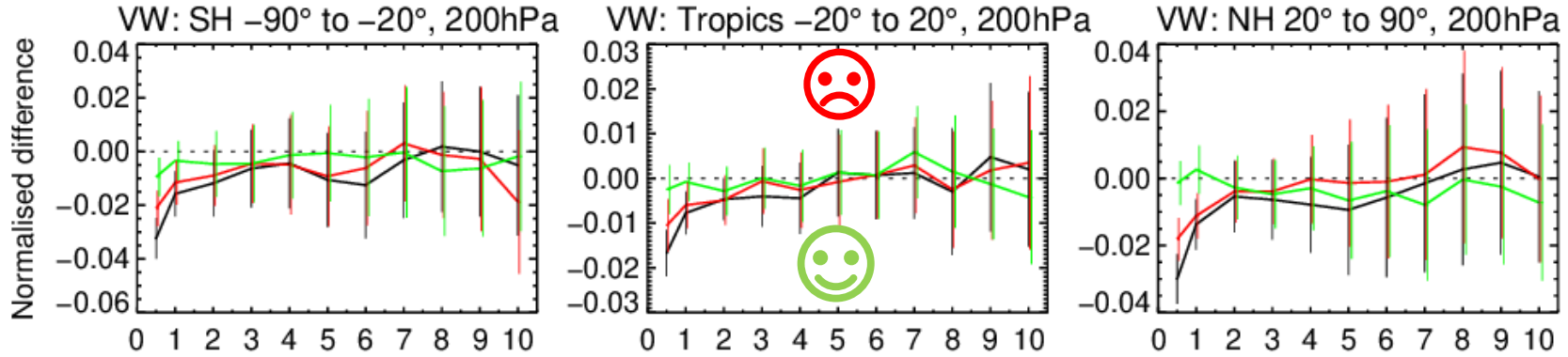
Geopotential RMSE 500 hPa



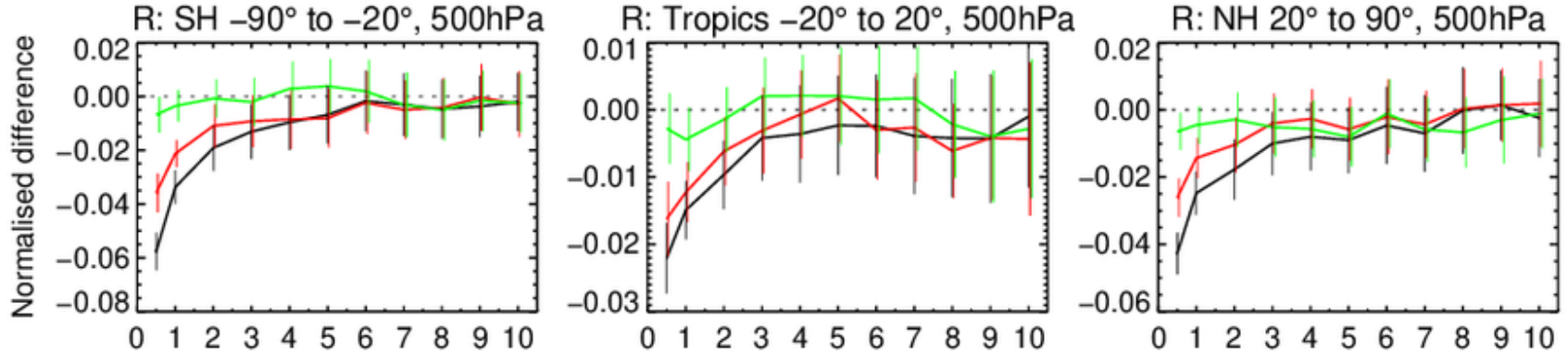
- 1 single outer loop is neutral
- Higher inner loop resolution significantly improves forecast skill through day 3

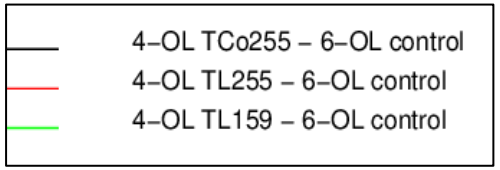
Impact on forecast skills

Vector wind RMSE 200 hPa



Relative Humidity RMSE 500 hPa



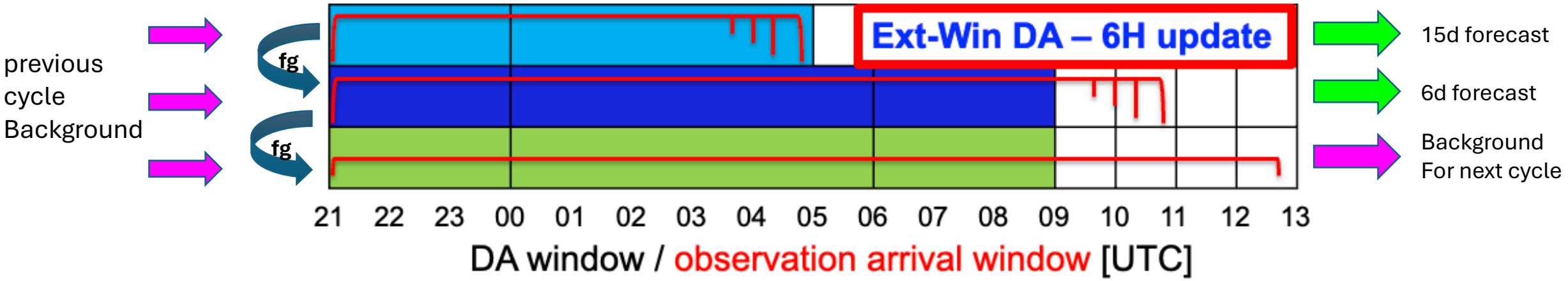


- 1 single outer loop is neutral
- Higher inner loop resolution significantly improves forecast skill through day 3

High resolution testing

High resolution / full suite

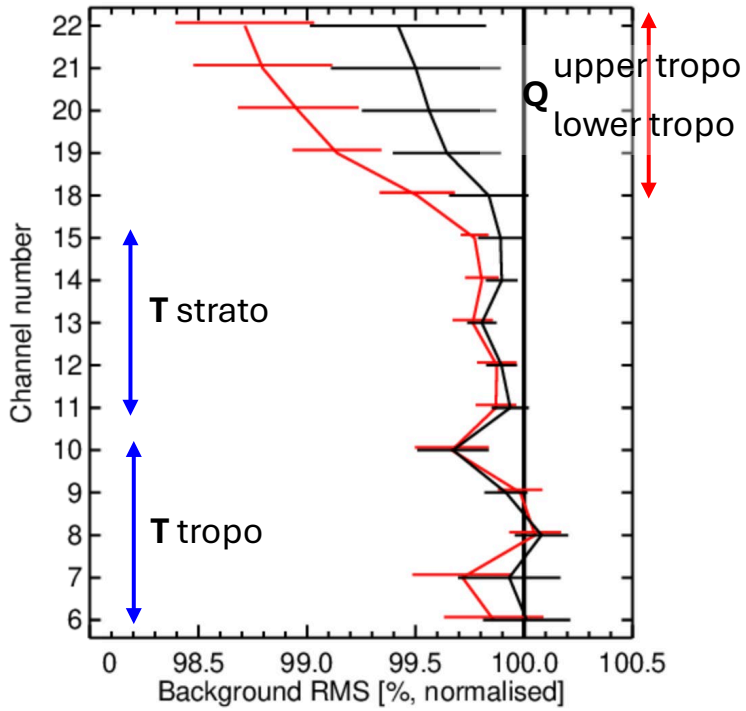
- Control: **4 + 4** outer loops
- Test: **4 + 4 + 1** outer loops
- Operational resolution experiments:
  Inner loop res. @ TL255/TL319/TL399/TL511 | Trajectory @ TCo1279



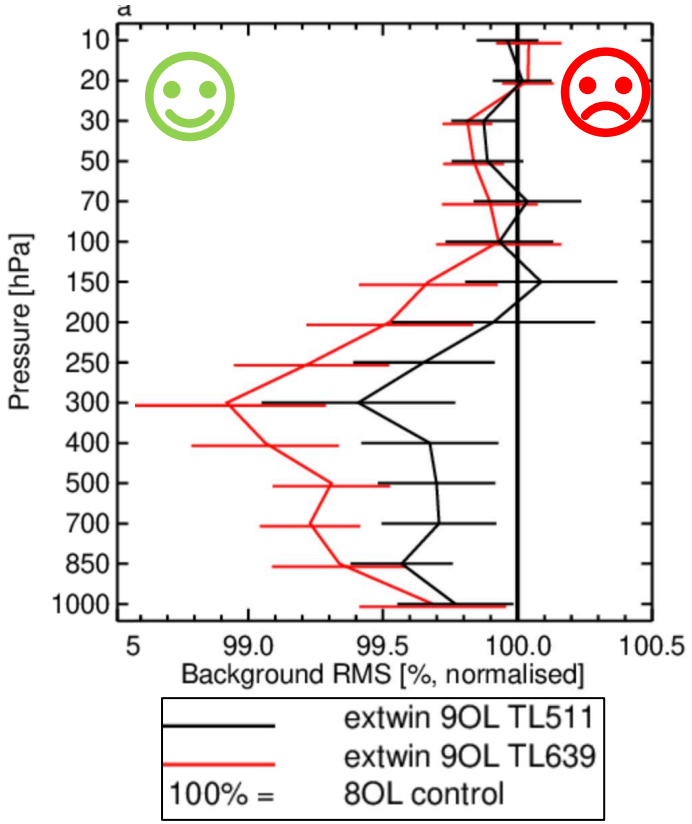
➢ Last analysis:
Testing one single outer loop @ TL511 (~40km) or TL639 (~31km)

High resolution testing – 8H window forecast skill

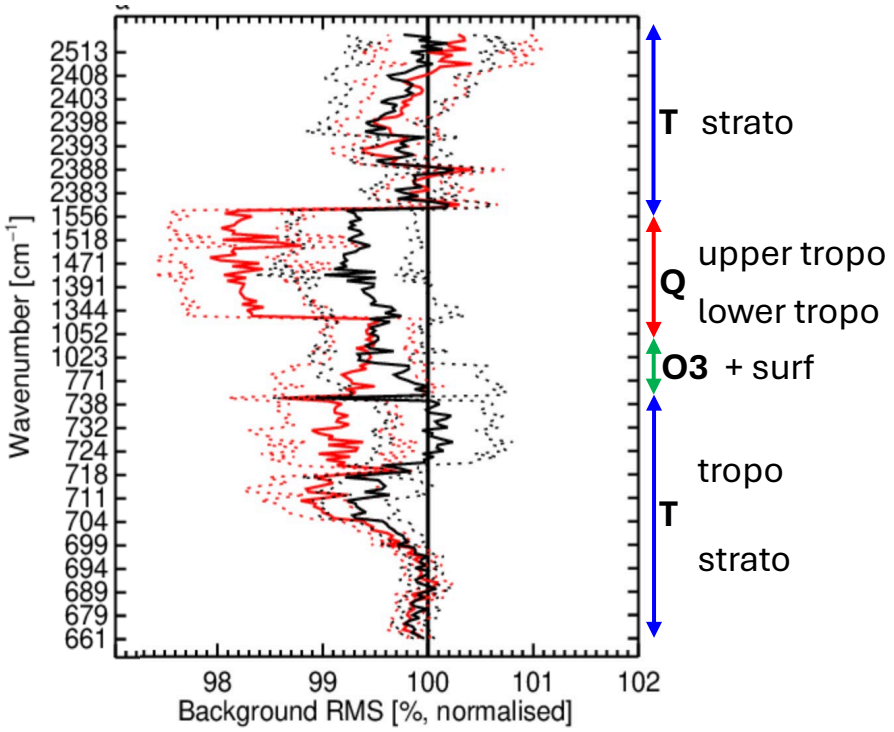
ATMS - global



Conventional wind - global



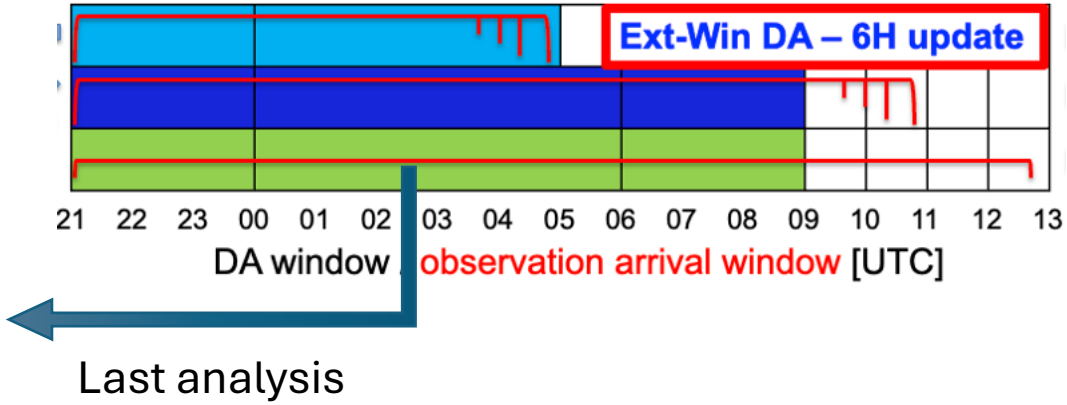
Hyperspectral IR - global



- Additional OL improves the short-range forecast skill through a better background.
- Trade-off between forecast skill and computational cost: TL639 vs TL511.

Computational footprint

OL iteration	Spectral truncation	Equatorial grid spacing (km)	Average Wall time (HH:mm)	Share of total wall time (%)
OL 1	TL255	78	00:20	16
OL 2	TL319	63	00:22	18
OL 3	TL399	50	00:27	22
OL 4	TL511	40	00:53	44
total			02:01	100



Using a **single outer loop** for the final analysis would save > 50% time
The resulting saving could be used to:

1. Relax the critical path to create the background for the next cycle; or
2. Increase the inner loop resolution
   e.g. TL 639 → ~ double wall time / still providing a small time saving

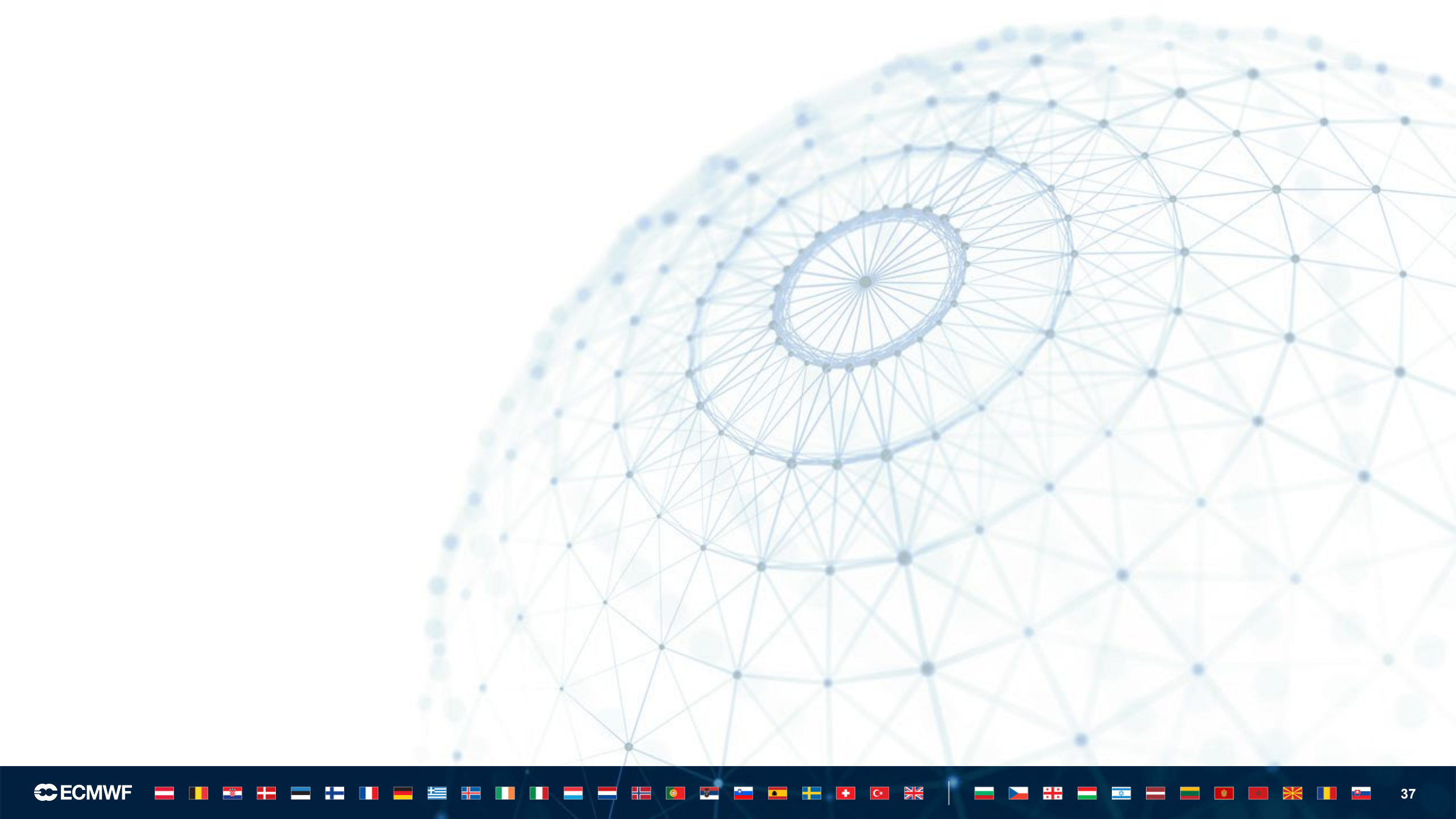
Conclusions and Outlook

Conclusions

- Observations arrive continuously, while operational global analyses are updated every 6 hours.
- Growing efforts across public institutions and the private sector aim to close this gap through more frequent forecast updates.
- Extending-window DA provides a pathway to more frequent global analyses within the established 4D-Var framework.
- It integrates the current DA configurations into a single system, with neutral-to-positive forecast impact and a better-distributed computational workload.

Outlook

- A 6-hourly extending-window configuration is proposed for the next IFS cycle.
- The framework opens a path towards 3-hourly analysis updates, supporting more timely forecasts for weather-critical applications.




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